Investigating the influence of the energy density distribution on the quality of laser sintered polyamide-12 parts by using X-Ray Computed Tomography

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Abstract
Laser sintering of polymers is an additive manufacturing technique used to produce layer by layer 3D polymeric objects. Laser sintered products are progressively used as functional parts in high quality standards sectors like the medical and automotive ones. During the process the melting of the polymeric powder is achieved thanks to the energy delivered by the CO_2 laser on the powder bed, which leads to progressive flow and densification of the material. However, the capabilities of the polymer to reach high densities and meet the dimensional tolerances required, strongly depends on the way the energy is delivered on the surface of the powder bed. In this work X-ray Computed Tomography is used to investigate the influence of the energy density distribution on the quality of laser sintered polyamide-12 parts, intended both as defects present in the microstructure and external dimensions.

Keywords: X-ray Computed Tomography, Laser Sintering, Porosity Analysis, Non-Destructive Testing, Quality Control, Energy Density Mapping, Dimensional Metrology

1. Introduction

Additive Manufacturing (AM) processes are increasingly being used to produce functional parts instead of prototypes. Laser Sintering (LS) is the most promising polymer processing technique that can aim to meet the quality requirements of the most demanding application sectors (ex. medical and automotive). However, some aspects of the LS process still need to be improved, in order to reduce the spread in part quality [1, 2] and to have a better control on the outcome of the process. The density and the final dimensions of the part depends on the way the energy is delivered on the surface of the powder bed by the CO_2 laser, namely to the process parameters and scanning strategy used. Inspecting the microstructural integrity and perform dimensional measurement of AM parts result sometimes difficult, especially for complex geometries. The unique capabilities of CT to inspect both the internal and external structures of workpieces allows to perform such a quality control, gathering information both about the porosity present within the LS object and to verify its dimensions and tolerances in a non-destructive way [3-6]. By correlating the information gathered through the analysis of the CT datasets with the local energy density (ED) distribution is possible to check the influence the process parameters and scanning pattern on the quality at the local scale. Literature offers a lot of studies about the influence of the ED on the quality of the PA12 LS parts, linking this parameter to residual porosity [4-7], crystallinity of the polymer [8-9] and mechanical properties [10-11]. However the ED is calculated as a global parameter, without taking into account its local variations due to overlap in the path of the vectors. Although the correlation between global ED and total porosity is widely reported in literature[4-7,9], it is still not clear whatever this correlation is valid at local scale, especially in regions close to the edge of the parts where the biggest ED variations have to be expected. In order to estimate the local ED distribution is necessary to combine all the parameters connected with the laser-scanning into a local ED mapping. By creating this ED map of the part to be built is possible to pre-assess the uniformity of the ED distribution, and possibly spot critical areas where the ED is too high (possible dimensional deviations) or too low (possible presence of porosity). The use of porosity maps [4-6], based on image processing of the CT slices of the printed part exported along the printing direction, allows to spot the areas most affected by porosity and to correlate them with the local ED distribution used to build a part. The aim of this paper is to investigate the correlation between the ED mapping quality control approach and the information gathered through the X-ray CT-based quality control. Figure 1 shows the workflow from data preparation till the printing of the part, highlighting at which stage of the printing process the two quality control approaches take place. As it is possible to see a validation of the ED mapping approach could give an early stage insight into the most evident printing problems and potentially reduce the number of iterations needed to successfully print a part which meets the quality requirements.

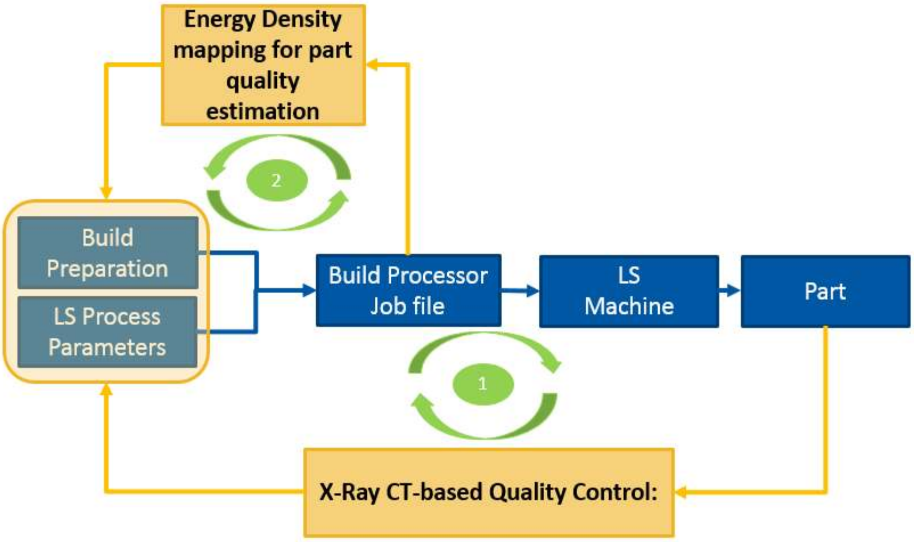


Figure 1 LS process workflow from data preparation till the printed part, where are highlighted the stages at where the two different quality control approaches act. (1) X-ray CT based quality control, (2) ED mapping based quality control.

2. Methods

The investigation on the influence of the local ED distribution on the printed quality of PA12 laser sintered product was performed on the simple test artefact showed in Figure 2. The object contain two features properly designed to address typical problems of the laser-based AM technologies like LS.

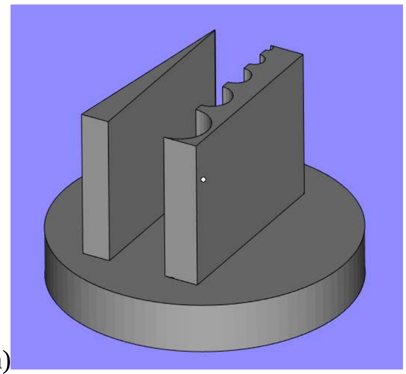
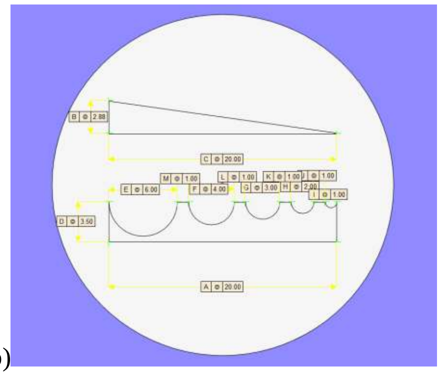
(a)  (b) 

Figure 2 Test artefact used to assess the correlation between the energy density distribution and the quality of the object; (a) lateral view, (b) top view with dimensions.

2.1 Sample production

The test artefact is produced in a state-of-the-art laser sintering machine, which has been equipped with the new Materialise Control Platform (MCP) [12] using a PA2200 PA12 powder with a mixing ratio 50/50 between virgin and recycled powder, a layer thickness of 120 microns and an alternate x-y scanning pattern. Table 1 resumes the laser scanning parameters used to print the part, with indicated the ED calculated according to Equation 1. According to the literature [4, 7-11] the ED value reported in Table 1 should ensure to obtain optimal microstructural (i.e. porosity and crystallinity) and mechanical properties.

Table 1 Laser scanning parameters used to print the test artefact.

Contour Power (W)	Contour Scan Speed (mm/s)	Hatching Laser Power (W) (LP)	Hatching Scan Speed (mm/s) (SS)	Hatching Distance (mm) (HD)	Hatching Energy Density (J/mm2)
30	3000	40	4000	0.3	0.0333

$$ED = \frac{LP}{SS * HD}$$

Equation 1 Equation for the calculation of the energy density, where: LP represents the laser power, SS the laser scanning speed and HD the hatching distance.

2.2 X-ray CT

All CT scans have been performed using a 225 k V CT machine from Nikon Metrology using a Molybdenum target, a voltage of 110 kV, a current of 127 µA and 3000 projections. The magnification used was x10 yielding to a voxel size of 20 µm, which according to [4-6] ensures a sufficiently accurate porosity measurement. The reconstruction of the projections into the voxel volume (in float 32 bit format) is performed using CT Pro 3D software from Nikon Metrology. The dataset are analyzed using VGstudio max v. 3.0 from Volume Graphics GmbH, where the dataset has been aligned with the original STL file used to produce the object in the same way this was positioned into the laser sintering machine, allowing in this way to export the CT slices along the printing direction. By performing image processing of the CT-slices following the method described in [4] it was possible to obtain cumulative porosity maps, which resumes the porosity information of all the CT slices into one map. These porosity maps are then correlated with the ED maps.

2.3 Energy Density mapping

The creation of an ED map takes into account the parameters linked with the laser scanning, simulating in this way the theoretical energy delivered on the build platform during the printing of the parts. The ED maps used in this work have a pixel size of 12.8 µm, which is smaller compared to the pixel size of the CT slices (20 µm).

3. Results and Discussion

In this section the two features of the test artefact will be presented separately, focusing on different problems connected with the LS printing process, namely: residual porosity and dimensional deviations from design. Figure 3 shows the x-and-y scanning pattern, the relative ED maps, the cumulative porosity map along the printing direction and a representative CT-slice of the polygon with a triangular base. It is common use in the LS process to apply an x-and-y scanning pattern, because it generally mitigate eventual disuniformities which can rise from a repetitive laser scanning pattern. The ED map relative to the y-scanning pattern shown in Figure 3 (2b) appears to be rather uniform, while the one shown in Figure 3 (1b) presents some areas with a lack of energy, due to an inefficient energy delivered mainly due to the difficult geometry of the feature. These lack of energy regions nicely correlate with the most porous areas present in the cumulative porosity map showed in Figure 3 (1c). This correlation suggests that an insufficient ED leads to an incomplete melting and coalescence of the PA12 particles, leading to a local higher porosity. This result confirms that the global correlation between ED and porosity widely reported in literature [4, 7-11] is also valid at the local level.

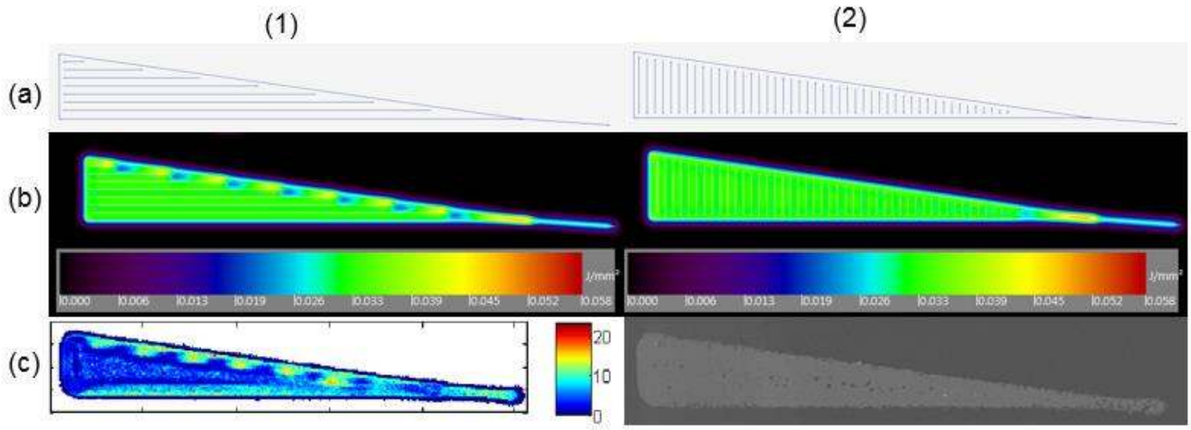


Figure 3 (1a) Scanning pattern with laser scanning vectors in x-direction; (2b) Scanning pattern with the laser scanning vectors in y-direction; (1b) ED map relative to scanning pattern showed in (1a); (2b) ED map relative to scanning pattern showed in (2a); (1c) Cumulative porosity map obtain from the CT slices exported along the printing direction; (2c) Representative CT slice exported along the printing direction.

Figure 4 shows y-scanning pattern, the relative ED map and a representative CT-slice. The ED map showed in Figure 4 (b) presents a region where the ED level rises well above the calculated value reported in Table 1. This global ED calculation obtained using the Equation 1 takes into account only parameters linked to the filling's vectors (also called hatching's vectors), namely it is valid only in conditions where the surface is completely covered by these vectors, while is not valid anymore close to the edges of the part, due to the presence of contour's vectors and due to the increased difficulties to deliver a homogeneous amount of energy when the geometry of the part gets more complex. The ED overshoot showed in Figure 4 (b) is due to the relative nearness of the laser paths compared to the actual laser beam diameter (0.6 mm), which determines an overlap in the laser tracks and, consequently, a higher local ED delivered. Comparing the high ED region with the sintered material visible in the CT-slice appears clear a consistent dimensional deviation. This result shows how the high local ED values determine dimensional deviations from the original design.

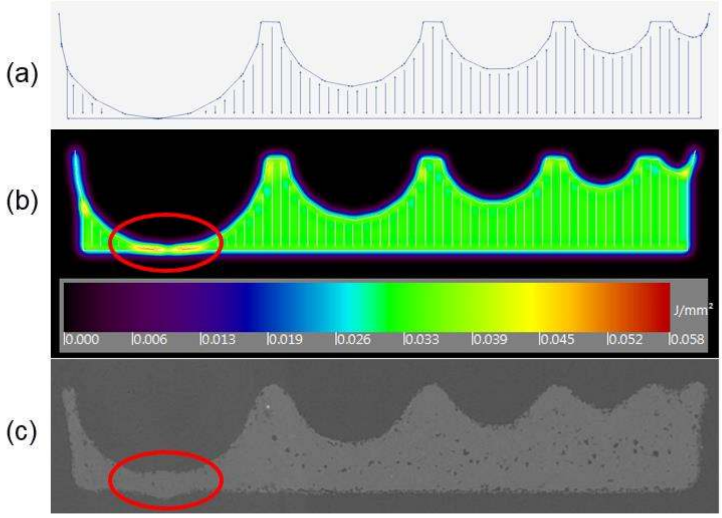


Figure 4 (a) Scanning pattern with laser scanning vectors in y-direction; (b) ED map relative to scanning pattern showed in (a); (c) Representative CT slice exported along the printing direction.

4. Conclusions

In this work it was investigated the capabilities of the local ED mapping to give insight on critical areas of the LS PA12 test object. Lack of energy regions have been correlated with a local higher porosity values, confirming the validity of the correlation between low ED and porosity at local scale. High ED areas have been proven to lead to significative dimensional deviations from the original design. Using the traditional global calculation of the ED would not permit to spot this critical regions, missing in this way important pre-build insight on the quality of the printed object. In fact a global ED takes into account only parameters linked to the filling's vectors (also called hatching's vectors), namely it is valid only in conditions where the surface is completely covered by these vectors, while is not valid anymore close to the edge of the part, especially when the geometry of the part gets more complex. In this areas a higher local variation of the ED has to be expected. The ED mapping based quality control of LS PA12 object was validated through the use of X-ray CT, giving in this way the possibility to a LS operator to perform a quick pre-assessment of the possible quality output before actually printing the parts. This approach potentially allows to lower the number of printing iterations before finding the optimal LS process parameters, especially for complex geometries.

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